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HD 3651 B: the first directly imaged brown dwarf companion of an exoplanet host star

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ABSTRACT

In the course of our ongoing multiplicity study of exoplanet host stars we detected a faint companion located at ~ 43 arcsec (480 AU physical projected separation) north-west of its primary — the exoplanet host star HD 3651 at 11 pc. The companion, HD 3651 B, clearly shares the proper motion of the exoplanet host star in our four images, obtained with ESO/NTT and UKIRT, spanning three years in epoch difference. The magnitude of the companion is $H = 16.75 \pm 0.16$ mag, the faintest co-moving companion of an exoplanet host star imaged directly. HD 3651 B is not detected in the POSS-II B-, R- and I-band images, indicating that this object is fainter than ~ 20 mag in the B- and R-band and fainter than ~ 19 mag in the I-band. With the Hipparcos distance of HD 3651 of 11 pc, the absolute magnitude of HD 3651 B is about 16.5 mag in the H band. Our H-band photometry and the Baraffe et al. (2003) evolutionary models yield a mass of HD 3651 B to be 20 to 60 M_{Jup} for assumed ages between 1 and 10 Gyr. The effective temperature ranges between 800 and 900 K, consistent with a spectral type of T7 to T8. We conclude that HD 3651 B is a brown-dwarf companion, the first of its kind directly imaged as a companion of an exoplanet host star, and one of the faintest T dwarfs found in the solar vicinity (within 11 pc).

Key words: stars: individual: HD 3651, stars: binaries: visual, brown dwarfs, planetary systems

1 INTRODUCTION

During the last decade high precision radial-velocity studies revealed almost 200 exoplanets around mainly solar-like stars located in the solar neighborhood. The stellar multiplicity of these planet host stars was already investigated by several groups using imaging data from visible and infrared all sky surveys like POSS or 2MASS, see e.g. Bakos et al. (2006) or Raghavan et al (2006). With seeing limited near infrared imaging (see e.g. Mugrauer et al. 2005 and 2006) as well as high contrast diffraction limited AO observations (e.g. Els et al. 2001, Patience et al. 2002, Luhman & Jayawardhana 2002, and Chauvin et al. 2006) further companions of exoplanet host stars have been detected during the last few years. Up to now, more than 30 companions of exoplanet host stars are known, suggesting that the multiplicity of these stars is at least 20 %.

Faint companions of exoplanet host stars were detected close to HD 114762 (Patience et al. 2002) and Gl 86 (Els et al. 2001) with angular separations smaller than 3 arcsec, which corresponds to physical projected separations of 130 and ~ 20 AU, respectively. In addition to these faint close objects, Wilson et al. (2001) reported a faint, wide companion to HD 89744, detected in the 2MASS point source catalogue (Skrutskie et al. 2006). HD 89744 B is located 63 arcsec (~ 2500 AU physical projected separation) north-east of HD 89744 A, and shares the proper motion of this exoplanet host star (Mugrauer et al. 2004). While the faint companions HD 114762 B ($M_H \sim 10.4$ mag) and HD 89744 B ($M_H \sim 11.1$ mag) are both very low-mass objects with masses of about 0.080 $M_\odot$, Gl 86 B ($M_H \sim 14.2$ mag) turned out to be a white dwarf (see Mugrauer & Neuhäuser 2005 for further details).

So far, substellar companions with masses significantly below the stellar/substellar mass border of 0.075 $M_\odot$ have

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not been directly detected as companions to rad-vel planet host stars, neither with AO nor seeing limited imaging. In contrast, radial-velocity studies have already revealed a number of brown-dwarf companions close to the exoplanet host stars e.g. HD 38529 (Fischer et al. 2003a), HD 168443 (Marcy et al. 2001), and HD 202206 (Correia et al. 2005), with minimum masses of $msin(i) = 12.7$, 17.2 and 17.4 M_{Jup}, respectively. While the brown-dwarf companions of HD 38529 and HD 168443 both revolve around the planet host star on orbits with semi-major axes which are at least 10 times wider than those of the detected exoplanets, the brown-dwarf companion of HD 202206 moves around the planet host star inside the planetary orbit. All of these systems are interesting examples which might point out that planet and brown-dwarf formation processes can occur around the same star at comparable distances (see Correia et. al. 2005 for further discussion).

In this letter we present the first direct imaged brown-dwarf companion of an exoplanet host star which we detected in the course of our multiplicity study. We show the results of our near infrared observations in section 2 and discuss the properties of this new very faint companion in section 3.

2 OBSERVATIONS

HD 3651 is a high proper motion nearby K0 dwarf, located at the border of the northern constellations Pegasus and Pisces. Its proper motion and parallax ($\mu_\alpha cos(\delta) = -461.09 \pm 0.75$ mas/yr, $\mu_\delta = -370.90 \pm 0.61$ mas/yr, and $\pi = 90.03 \pm 0.72$ mas) are determined by Hipparcos (Perryman et al. 1997), yielding a distance of ~ 11 pc. According to Fischer et al. (2003b) HD 3651 is chromospheric inactive and photometrically stable, as expected for a middle-aged early K dwarf. The stellar radial velocity shows a periodical modulation with a period of 62.23 day, indicating the star is orbited by a sub-Saturn mass planet ($msin(i) = 0.20\,M_{Jup}$) with an eccentric ($e = 0.63$) orbit and a semi-major axis of $a = 0.284$ AU. According to Santos et al. (2004) HD 3651 exhibits an effective temperature of 5173 ± 35 K and a surface gravity of $log(g) = 4.37 \pm 0.12$ cm/s^2, as it is expected for an early K dwarf. Its metallicity is slightly enhanced compared to the sun ($[Fe/H] = 0.12 \pm 0.04$), typical for a planet host star. Santos et al. (2004) also derive the mass of HD 3651 to be 0.76 $M_\odot$, consistent with the mass estimate of 0.79 $M_\odot$ from Fischer et al. (2003b).

The age of this exoplanet host star has been estimated by several groups. Valenti et al. (2005) report an age between 3 and 12.5 Gyr, derived with isochron fitting. This range is consistent with the chromospheric age estimates of 5.9 Gyr from Wright et al. (2004) and 2.1 Gyr from Rocha-Pinto et al. (2004).

HD 3651 is a target of our imaging search campaign for visual companions of northern exoplanet host stars which was carried out with the 3.8 m United Kingdom Infrared Telescope (UKIRT), located at Mauna Kea (Hawaii). We observed HD 3651 in the H-Band with the infrared camera UKIRT Fast Track Imager (UFTI) a 1024×1024 HgCdTe infrared detector with a pixel scale of ~ 91 mas per pixel and 93 arcsec $\times$ 93 arcsec field of view. The first epoch imaging is carried out in June 2003. In order to reduce strong saturation effects of the bright exoplanet host star the shortest available integration time (4 s) was used and six of these 4 s integrations were averaged to one image. The standard jitter/dither technique was applied to minimize the sky background.

In total 22 jitter positions were chosen, resulting in a total integration time of 8.8 min. The ESO package *ECLIPSE* (Devillard 2001) was used for background estimation and subtraction as well as the flat fielding of all images which where finally combined by shift+add.

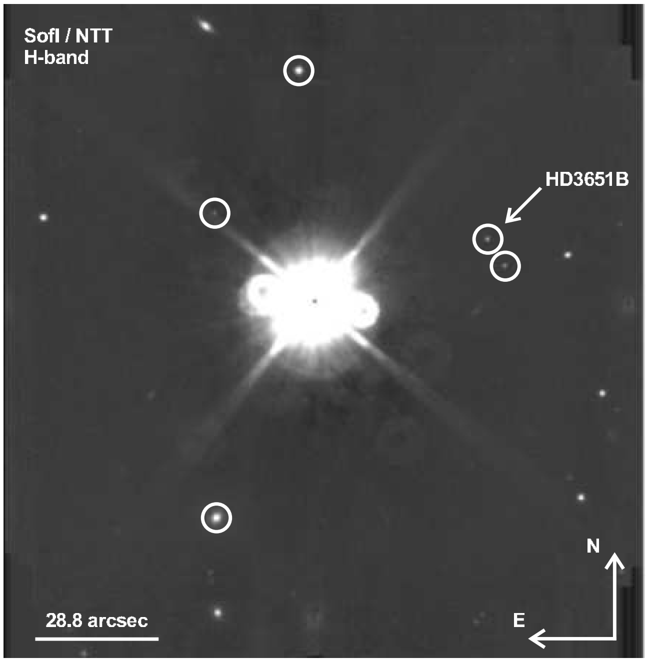
In addition to HD 3651 we observed many other exoplanet host stars in that run. With all these images we can derive the astrometric calibration of the UFTI detector using the 2MASS point source catalogue (Skrutskie et al. 2006), which contains accurate positions of objects brighter than 15.2 mag in H ($S/N > 5$). The derived pixel scale and detector orientation of all observing runs presented here are summarized in Tab. 1. The achieved detection limit ($S/N > 10$) of the UFTI observations is H$\sim$18.4 mag which is reached in the background noise limited region at angular separations larger than 15 arcsec around the bright exoplanet host star.

Five faint objects around HD 3651 are detected in our UFTI image, all of which might be real companions of the exoplanet host star. With a follow-up 2nd epoch observation we tested the companionship of the detected companion-candidates. Real companions of the exoplanet host star would share the proper motion of their primary, as their orbital motion is much smaller than the proper motion of the exoplanet host star. Such co-moving companions can therefore be easily distinguished from non- or slowly moving background stars by comparing two images taken with sufficient long time difference.

The 2nd epoch UFTI observation of HD 3651 was obtained in October 2003. We averaged again six 4 s integrations per jitter-position but chose this time a 24 position jitter pattern, yielding a total integration time of 9.6 min.

Although the time difference between the two UFTI observations is only 4 months, the astrometric companion search is already feasible because of the high proper motion of HD 3651, which amounts to 0.6 arcsec/yr. All candidates except one significantly change their separations and position angles relative to the exoplanet host star. Only one candidate does not show a significant variation in its position angle and separation. Its relative astrometry is summarized in Tab. 1, and is illustrated in Fig. 2. This object might be a real companion of the exoplanet host star, and therefore is being denoted as HD 3651 B henceforth.

Due to the proximity of HD 3651, which is located only at a distance of 11 pc, the UFTI field of view allows only the detection of companions with physical projected separations up to ~ 500 AU from the exoplanet host star. In order to reach wider companions we include HD 3651 in our companion search program of southern exoplanet host stars and nearby stars, both being carried out at La Silla observatory with the ESO 3.58 m New Technology Telescope (NTT) and its infrared camera SofI, a 1024×1024 HgCdTe-detector. All observation were obtained again in the H-band using the SofI small field objective with its pixel scale of 144 mas per pixel, yielding a field of view of 147×147 arcsec. This allows the detection of wide companions around HD 3651 with physical projected separations up to ~ 800 AU. Our 1st epoch SofI observation of HD 3651 was carried out in



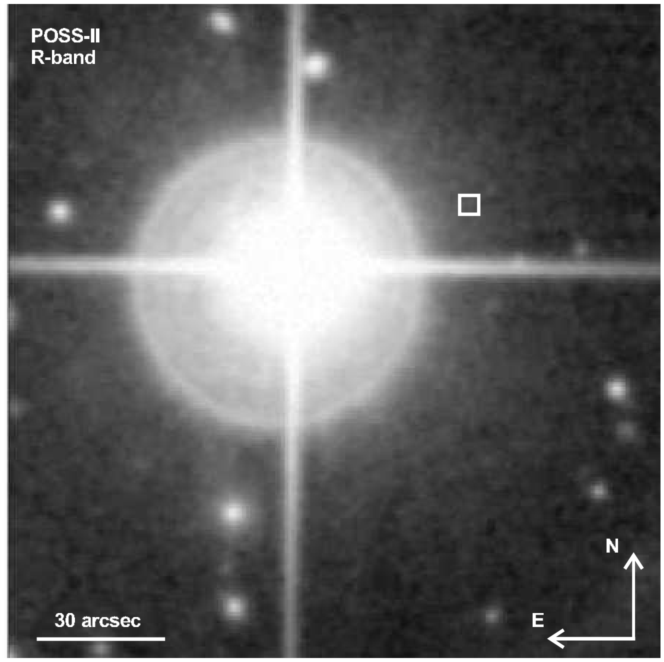


Figure 1. Left pattern: The SofI small field image of the planet host star HD 3651, taken in June 2006 in the H-band. All companion candidates which are also detected in our UFTI H-band images are marked with white circles. The co-moving companion HD 3651 B is indicated with a black arrow. Right pattern: The exoplanet host star HD 3651 detected on the R-band POSS-II photographic plate from observing epoch August 1987. Faint objects are detected around HD 3651 with magnitudes down to ~ 21 mag. The expected position of HD 3651 B is illustrated with a white box but the companion is not detected in the POSS image. The motion of the exoplanet host star relative the background sources is already visible by comparing the POSS image with our SofI image.

Table 1. The pixel scale and the detector orientation with their uncertainties as well as the average seeing for all UFTI and SofI observing runs. The detector is tilted by the given angle from north to west. Furthermore, the separations and position angles of HD 3651 B relative to its primary — the exoplanet host star HD 3651 and the H-band photometry of the companion are listed, as measured in all UFTI and SofI observing epochs.

Epoche Camera & Date	Pixel Scale [arcsec/Pixel]	Detector Orientation [°]	seeing [arcsec]	separation [arcsec]	position angle [°]	H magnitude [mag]
UFTI 06/03	0.09109±0.00035	0.747±0.096	0.66	42.92±0.17	289.92±0.24	16.58±0.07
UFTI 10/03	0.09104±0.00030	0.711±0.083	0.69	43.15±0.14	289.99±0.21	16.83±0.07
SofI 07/04	0.14356±0.00011	90.047±0.024	1.25	42.89±0.08	289.92±0.10	16.93±0.10
SofI 06/06	0.14348±0.00016	90.017±0.049	0.73	43.07±0.08	289.97±0.11	16.65±0.07

July 2004. The 2nd epoch follow-up imaging was recently taken in June 2006. In both observing epochs we used the jitter technique and obtain 10 images, each the average of 50 1.2 s integrations, i.e. 10 min of total integration time. Our 2nd epoch SofI image is shown in the left pattern of Fig. 1.

Both SofI images are calibrated with the 2MASS point source catalogue (see Tab. 1). HD 3651 B and the 4 objects already detected in the UFTI images as well as several more wider companion candidates are found in the SofI images. However, all of these additional companion candidates exhibit only negligibly small proper motions, determined by the comparison of both SofI images. In contrast, HD 3651 B clearly shares the proper motion of HD 3651 A and its separation and position angle does not change during three years of epoch difference between the first UFTI observation (epoch 06/03) and the 2nd epoch SofI imaging (epoch 06/06), hence this is a real companion of the exoplanet host star (see Fig. 2).

The reached detection limit of our SofI observations for a range of separations to the planet host star is shown in Fig. 3. We are sensitive to companions with apparent H-Band magnitudes of 17.5 mag in the background noise limited region, i.e. at angular separations larger 16 arcsec ($\sim$ 180 AU) around the bright exoplanet host star. According to the Baraffe et al. (2003) models and the magnitude-mass relation therein, the achieved limiting magnitude allows the detection of brown-dwarf companions with a mass m $\geqslant 37\,M_{Jup}$ for an assumed age of the primary of 5 Gyr. Additional stellar companions (m$\geqslant 75\,M_{Jup}$) can be ruled out beyond 4.5 arcsec ($\sim$ 50 AU) up to separations of $\sim$ 760 AU. All objects within 69 arcsec around the exoplanet host star are imaged in both SofI observing epochs but, expect HD 3651 B, no further co-moving companions are detected.

We determine the apparent H-band magnitude of the co-moving companion HD 3651 B in all UFTI and SofI images, all of which are listed in Tab. 1. We measure the

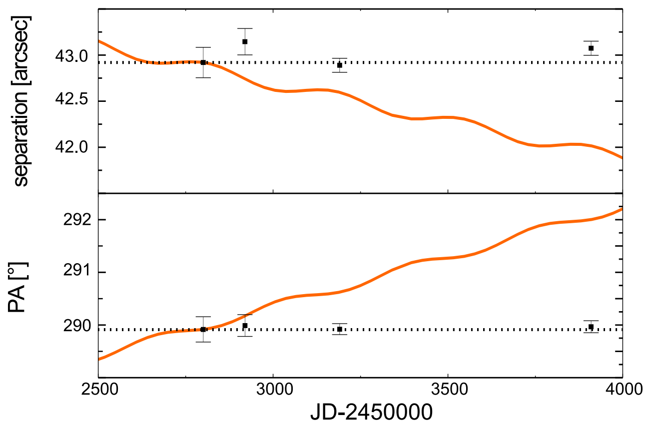


Figure 2. The separations and position angles of HD 3651 B relative to HD 3651 for all UFTI and SofI observing epochs. The solid line indicates the expected variation of separation and position angle in case HD 3651 B is a non-moving background star, calculated with the Hipparcos proper and parallactic motion of the exoplanet host star.

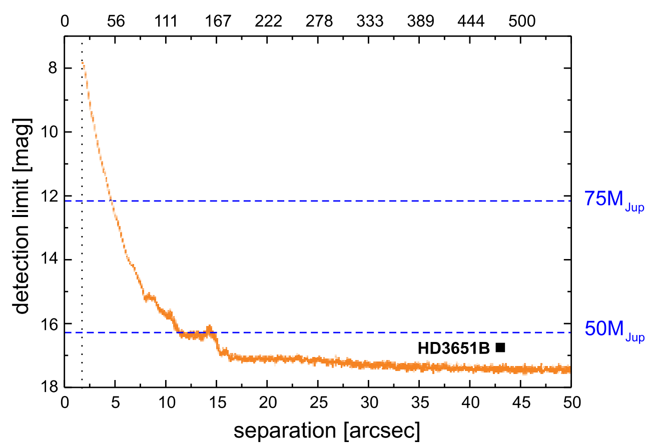


Figure 3. The detection limit ($S/N = 10$) of the SofI H-band imaging of the exoplanet host star HD 3651 plotted for a range of separations given in arcsec at the bottom and as physical projected separation in AU at the top. At $\sim$ 1.8 arcsec (20 AU) saturation occurs (doted line). At a system age of 5 Gyr the achieved limiting magnitude allows the detection of substellar companions with a mass m $\geqslant 37\,M_{Jup}$ in the background limited region beyond 16 arcsec ($\sim$ 180 AU). All stellar companions (m $\geqslant 75\,M_{Jup}$) are detectable beyond the distance illustrated by the upper dashed line ($\sim$ 50 AU). The faint co-moving companion HD 3651 B is plotted as a black square.

companion magnitude with aperture photometry using the data reduction package ESO-MIDAS. The photometric zero points of the observations are derived with sources detected in our UFTI and SofI images whose H-band magnitude is listed in the 2MASS point source catalogue. The averaged apparent H-band magnitude of the companion is $H = 16.75 \pm 0.16$ mag. The Hipparcos parallax $\pi = 90.03 \pm 0.72$ mas of the exoplanet host star finally yields an absolute magnitude of $M_H = 16.52 \pm 0.16$ mag.

3 ON THE NATURE OF HD 3651 B

Our H-band multi-epoch UFTI and SofI observations of the exoplanet host star HD 3651 revealed the faint co-moving companion HD 3651 B, separated from its primary by 43 arcsec, corresponding to physical projected separation of $\sim$ 480 AU. With an apparent H-band magnitude of $H = 16.75 \pm 0.16$ mag, HD 3651 B is the faintest co-moving companion of an exoplanet host star detected so far. Up to now the faintest known companion of an exoplanet host star is Gl 86 B, whose absolute H-band magnitude was measured by Els et al. (2001) to be $M_H = 14.2 \pm 0.2$ mag. With its absolute H-band magnitude of $M_H \sim 16.5$ mag, HD 3651 B is 2.3 mag fainter than Gl 86 B.

HD 3651 B is detected in our near infrared UFTI and SofI images but we do not find a visible counterpart on the photographic B-, R-, and I-band plates of the 2nd Palomar All Sky Survey (POSS-II). The POSS-II R-band plate is shown in the right pattern of Fig. 1. According to Griffin (2002) the detection limit of the POSS-II plates are 22.5 mag in B-band, 20.8 mag in R-band, and 19.5 mag in I-band. Hence, HD 3651 B has to be fainter than $\sim$ 20 mag in R- and B-band and fainter than $\sim$ 19 mag in the I-band to remain undetectable on all POSS plates.

HD 3651 B is a faint source in the near infrared H-band and it is not detectable in the B-, R- and I-band. Due to its faintness in the optical spectral range compared to its near infrared H-band photometry, HD 3651 B is not a cool white dwarf which is expected to be comparable bright in all photometric bands (see Bergeron et al. 1995), i.e. should be detectable on the POSS plates. In contrast, according to the evolutionary models of low-mass substellar objects from Baraffe et al. (2003) all these photometric results are fully consistent with a cool brown dwarf located at the distance of the exoplanet host star. With this models we can also derive the physical properties of HD 3651 B from the measured H-band absolute magnitude assuming different system ages. In Tab. 2 we have summarized the derived companion masses and effective temperatures as well as the expected absolute R- and I-band magnitudes for assumed ages of 1, 5 and 10 Gyr (B-band magnitudes not given in theses models). The mass ranges from 22 up to 57 M_{Jup} for an age of 1 and 10 Gyr, respectively. The expected effective temperature of the brown dwarf ranges between 800 and 900 K. According to Golimowski et al. (2004) the derived temperature range is consistent with a spectral type of T7. Furthermore, if we use the M_H versus spectral type relation, derived by Vrba et al. (2004), the absolute magnitude of HD 3651 B is consistent with a brown dwarf of spectral type T7.9. Follow-up spectroscopy would be interesting to confirm the spectral type.

After ϵ Ind B (McCaughrean et al. 2004) and SCR 1845-6357 B (Biller et al. 2006) HD 3651 B is a further late T dwarf in the solar neighborhood. Its companionship to an exoplanet host star is especially remarkable and puts news constraints to the formation theory of brown dwarfs and extrasolar planets. This finding is a further evidence that both formation process can occur around the same object.

Table 2. The mass and effective temperature of HD 3651 B as well as its expected R- and I-band magnitudes derived from our UFTI and SofI H-band photometry and the Baraffe et al. (2003) evolutionary models.

age	[Gyr]	1	5	10
mass	$[M_{Jup}]$	22±1	46±2	57±2
T_{eff}	[K]	798±25	855±26	885±26
M_R	[mag]	22.80±0.10	22.86±0.08	22.90±0.08
M_I	[mag]	20.01±0.10	20.08±0.09	20.11±0.09

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